

DOUBLE BETA DECAY EXPERIMENTS: BEGINNING OF A NEW ERA

A.S. Barabash^{1,*}

*¹Institute of Theoretical and Experimental Physics,
B. Cheremushkinskaya 25, 117218 Moscow, Russia*

Abstract

The review of current experiments on search and studying of double beta decay processes is done. Results of the most sensitive experiments are discussed and values of modern limits on effective Majorana neutrino mass ($\langle m_\nu \rangle$) are given. New results on two neutrino double beta decay are presented. The special attention is given to new current experiments with mass of studied isotopes more than 100 kg, EXO-200 and KamLAND-Zen. These experiments open a new era in research of double beta decay. In the second part of the review prospects of search for neutrinoless double beta decay in new experiments with sensitivity to $\langle m_\nu \rangle$ at the level of $\sim 0.01 - 0.1$ eV are discussed. Parameters and characteristics of the most perspective projects (CUORE, GERDA, MAJORANA, SuperNEMO, EXO, KamLAND-Zen, SNO+) are given.

PACS numbers: 23.40.-s, 14.60.Pq

*Electronic address: barabash@itep.ru

I. INTRODUCTION

Interest in $0\nu\beta\beta$ decay has seen a significant renewal in recent 10 years after evidence for neutrino oscillations was obtained from the results of atmospheric, solar, reactor, and accelerator neutrino experiments. These results are impressive proof that neutrinos have a nonzero mass. The detection and study of $0\nu\beta\beta$ decay may clarify the following problems of neutrino physics: (i) lepton number non-conservation, (ii) neutrino nature: whether the neutrino is a Dirac or a Majorana particle, (iii) absolute neutrino mass scale (a measurement or a limit on m_1), (iv) the type of neutrino mass hierarchy (normal, inverted, or quasidegenerate), (v) CP violation in the lepton sector (measurement of the Majorana CP-violating phases).

Progress in the double beta decay is connected with increase in mass of a studied isotope and sharp reduction of a background. During a long time (1948–1980) samples with mass of isotope ~ 1 –25 grams were used. So, for example, the first observation of a two neutrino double beta decay in direct (counting) experiment has been done in 1987 when studying 14 g of enriched ^{82}Se [1]. And only in the 80th - beginning of the 90th the mass of studied isotope increased to hundred grams and even to 1 kg. In the 90th Heidelberg-Moscow [2] and IGEX [3] experiments, containing 11 kg and 6.5 kg of ^{76}Ge , respectively, were started. In zero years the NEMO-3 [4] and CUORICINO [5] installations, containing approximately 10 kg of isotopes (7 kg of ^{100}Mo , 1 kg of ^{82}Se , etc. in NEMO-3 and 40 kg of crystals from a natural oxide of Te, containing 10 kg of ^{130}Te , in CUORICINO) set the fashion.

In 2011 the EXO-200 [6] and KamLAND-Zen [7] experiments have been started (in which hundreds kilograms of ^{136}Xe are used). Soon it is planned to carry out start of several more experiments with mass of studied isotopes ~ 100 kg (SNO+ [8], CUORE [9], etc.). And it means the beginning of a new era in 2β decay experiments when sensitivity to effective Majorana mass of neutrino will reach for the first time values < 0.1 eV.

Structure of the review is the following: in section II current large-scale experiments on $\beta\beta$ decay are considered, in section III the most perspective planned experiments are discussed, the best modern limits on neutrino mass and the forecast for possible progress in the future are given in section IV (Conclusion).

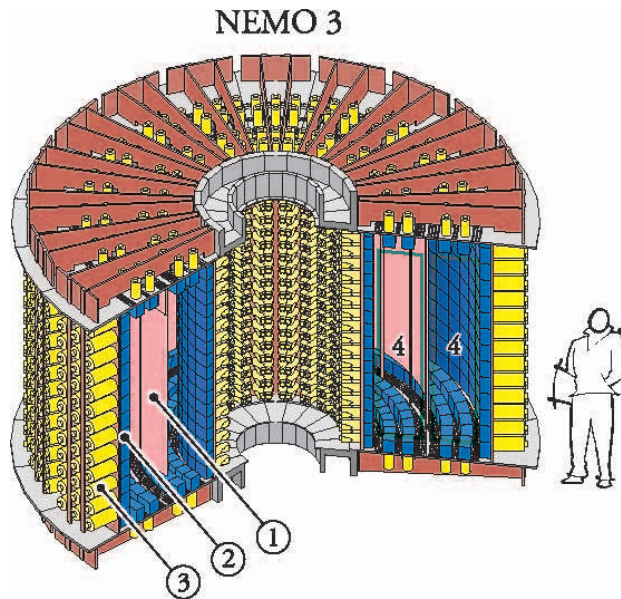


FIG. 1: The NEMO-3 detector without shielding [10]. 1 – source foil; 2– plastic scintillator; 3 – low radioactivity PMT; 4 – tracking chamber.

II. CURRENT LARGE-SCALE EXPERIMENTS

In this section the current large-scale experiments are discussed. NEMO-3 experiment was stopped in January, 2011, but data analysis in this experiment proceeds and consequently it should be carried to the current experiments.

A. NEMO-3 [4, 10]

This tracking experiment, in contrast to experiments with ^{76}Ge , detects not only the total energy deposition, but other parameters of the process, including the energy of the individual electrons, angle between them, and the coordinates of the event in the source plane. Since June of 2002 and to January of 2011, the NEMO-3 detector has been operated in the Frejus Underground Laboratory (France) located at a depth of 4800 m w.e. The detector has a cylindrical structure and consists of 20 identical sectors (see Fig. 1). A thin ($30\text{--}60\text{ mg/cm}^2$) source containing double beta decaying nuclei and natural material foils have a total area of 20 m^2 and a weight of up to 10 kg was placed in the detector. The energy of the electrons is measured by plastic scintillators (1940 individual counters), while

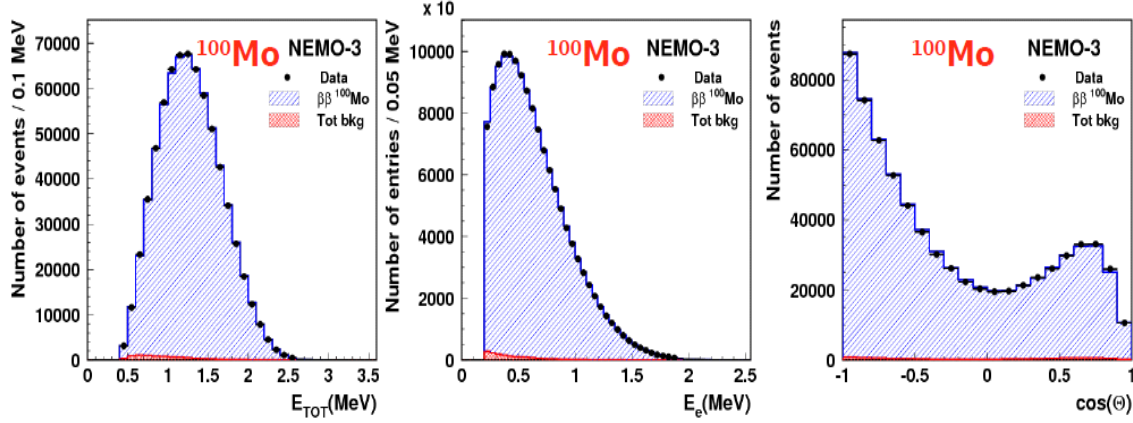


FIG. 2: Total energy, individual energy and angular distributions of the ^{100}Mo 2ν events in the NEMO-3 experiment for the low radon Phase-II data (4 years) [10].

the tracks are reconstructed on the basis of information obtained in the planes of Geiger cells (6180 cells) surrounding the source on both sides. The main characteristics of the detector are the following. The energy resolution of the scintillation counters lies in the interval 14-17% FWHM for electrons of energy 1 MeV. The time resolution is 250 ps for an electron energy of 1 MeV and the accuracy in reconstructing the vertex of $2e^-$ events is 1 cm.

Measurements with the NEMO-3 detector revealed that tracking information, combined with time and energy measurements, makes it possible to suppress the background efficiently. Using the NEMO-3 installation 7 isotopes ^{100}Mo (6.9 kg), ^{82}Se (0.93 kg), ^{116}Cd (405 g), ^{150}Nd (36.6 g), ^{96}Zr (9.4 g), ^{130}Te (454 g) and ^{48}Ca (7 g) are investigated. A full description of the detector and its characteristics can be found in [4].

Figure 2 display the spectrum of $2\nu\beta\beta$ events for ^{100}Mo that were collected over 4 years (low radon Phase II). The angular distribution and single electron spectrum are also shown. The total number of events exceeds 700000 which is much greater than the total statistics of all of the preceding experiments with ^{100}Mo (and even greater than the total statistics of all previous $2\nu\beta\beta$ decay experiments!). It should also be noted that the background is as low as 1.3% of the total number of $2\nu\beta\beta$ events. Measurements of the $2\nu\beta\beta$ decay half-lives have been performed for seven isotopes available in NEMO-3. The NEMO-3 results of $2\nu\beta\beta$ half-life measurements are given in Table I (only part of full statistic has been analysed). For all the isotopes the energy sum spectrum, single electron energy spectrum and angular distribution were measured. The ^{100}Mo double beta decay to the 0_1^+ excited state of ^{100}Ru

has also been measured by NEMO-3 [14]. For ^{100}Mo , ^{82}Se , ^{96}Zr , ^{150}Nd and ^{130}Te these intermediate results are published. For the other isotopes their status is preliminary.

TABLE I: Present results from NEMO-3 (only part of full statistic has been analysed). All limits are presented at a 90% C.L.

Isotope	$T_{1/2}(2\nu)$, yr	$T_{1/2}(0\nu)$, yr	$T_{1/2}(0\nu\chi^0)$, yr
^{100}Mo	$(7.11 \pm 0.02 \pm 0.54) \cdot 10^{18}$ [11]	$> 1.1 \times 10^{24}$ [12]	$> 2.7 \times 10^{22}$ [13]
$^{100}\text{Mo-}$	$(5.7^{+1.3}_{-0.9} \pm 0.8) \cdot 10^{20}$	$> 8.9 \times 10^{22}$	-
$^{100}\text{Ru } (0_1^+)[14]$			
^{82}Se	$(9.6 \pm 0.3 \pm 1.0) \cdot 10^{19}$ [11]	$> 3.6 \times 10^{23}$ [12]	$> 1.5 \times 10^{22}$ [13]
^{130}Te [15]	$(7.0 \pm 0.9 \pm 1.1) \cdot 10^{20}$	$> 1.3 \times 10^{23}$	$> 1.6 \times 10^{22}$
^{150}Nd [16]	$(9.11^{+0.25}_{-0.22} \pm 0.63) \cdot 10^{18}$	$> 1.8 \times 10^{22}$	$> 1.52 \times 10^{21}$
^{96}Zr [17]	$(2.35 \pm 0.14 \pm 0.16) \cdot 10^{19}$	$> 9.2 \times 10^{21}$	$> 1.9 \times 10^{21}$
^{116}Cd	$(2.88 \pm 0.04 \pm 0.16) \cdot 10^{19}$	$> 1.3 \times 10^{23}$	-
^{48}Ca	$(4.4^{+0.5}_{-0.4} \pm 0.4) \cdot 10^{19}$	$> 1.3 \times 10^{22}$	-

No evidence for $0\nu\beta\beta$ decay was found for all seven isotopes. The associated limits are presented in Table I. Best limit has been obtained for ^{100}Mo ($T_{1/2}^{0\nu} > 1.1 \cdot 10^{24}\text{yr}$). Corresponding limit on the neutrino mass is $\langle m_\nu \rangle < 0.29 - 0.7$ eV (using nuclear matrix element (NME) values from [18–22]). No evidence for decay with Majoron emission ($0\nu\chi^0\beta\beta$) was found for all seven isotopes too. The limits for ^{100}Mo , ^{82}Se , ^{150}Nd , ^{96}Zr and ^{130}Te are presented in Table I. In particular, strong limits on ordinary Majoron (spectral index 1) decay of ^{100}Mo ($T_{1/2} > 2.7 \cdot 10^{22}$ y) and ^{82}Se ($T_{1/2} > 1.5 \cdot 10^{22}$ y) have been obtained. Corresponding bounds on the Majoron-neutrino coupling constant have been established, $< g_{ee} > < (0.25 - 0.67) \cdot 10^{-4}$ and $< (0.6 - 1.9) \cdot 10^{-4}$, respectively (using nuclear matrix elements from [18–24]).

Data analysis proceeds and Collaboration hope for receiving final results for all 7 isotopes in the nearest future (2012–2013).

B. EXO-200 [6, 25]

EXO-200 (Enriched Xenon Observatory) is operating at the Waste Isolation Pilot Plant (WIPP, 1585 m w.e.) since May 2011. The experiment consists of 175 kg of Xe enriched to 80.6% in ^{136}Xe housed in a liquid time projection chamber (TPC). The TPC is surrounded by passive and active shields. This detector measures energy through both ionization and scintillation and is capable of effectively rejecting rays through topological cuts. EXO-200 has recently claimed the first observation of $2\nu\beta\beta$ in ^{136}Xe ($Q_{\beta\beta} = 2458.7$ keV) [6]. Initial results on $0\nu\beta\beta$ decay together with new result for 2ν mode are published in [25]. The fiducial volume used in this analysis contains 79.4 kg of ^{136}Xe ($3.52 \cdot 10^{26}$ atoms), corresponding to 98.5 kg of active ^{enr}LXe . Energy resolution is 10.5 % (FWHM) at 2.615 MeV using ionization signal only and 4% (FWHM) using both ionization and scintillation signals. Background index (BI) in the 0ν region is $1.4 \cdot 10^{-3}$ counts/keV·kg·yr (see Fig. 3). Results obtained after 2896.6 h of measurements are the following:

$$T_{1/2} (2\nu, ^{136}\text{Xe}) = [2.23 \pm 0.017(stat) \pm 0.22(syst)] \cdot 10^{21} \text{yr} \quad (1)$$

$$T_{1/2} (0\nu, ^{136}\text{Xe}) > 1.6 \cdot 10^{25} \text{yr} \quad (90\% \text{ C.L.}) \quad (2)$$

Last result provides upper limit $\langle m_\nu \rangle < 0.14\text{--}0.38$ eV using NME values from [18–20, 22, 24]). Taking into account present background one can predict that EXO-200 sensitivity after 5 years of data taking will be $T_{1/2} \sim 4 \cdot 10^{25}$ yr ($\langle m_\nu \rangle \sim 0.09\text{--}0.24$ eV).

The project is also a prototype for a planned 1 ton sized experiment that may include the ability to identify the daughter of ^{136}Ba in real time, effectively eliminating all classes of background except that due to 2ν decay (see Section III. E).

C. KamLAND-Zen [7, 26]

The detector KamLAND-Zen (Fig. 4) is a modification of the existing KamLAND detector carried out in the summer of 2011. The $\beta\beta$ source/detector is 13 tons of Xe-loaded liquid scintillator (Xe-LS) contained in a 3.08 m diameter spherical inner balloon (IB). The IB is constructed from 25 μm thick transparent nylon film and is suspended at the center of the KamLAND detector by 12 film straps of the same material. The IB is surrounded by 1 kton of liquid scintillator (LS) contained in a 13 m diameter spherical outer balloon (OB) made

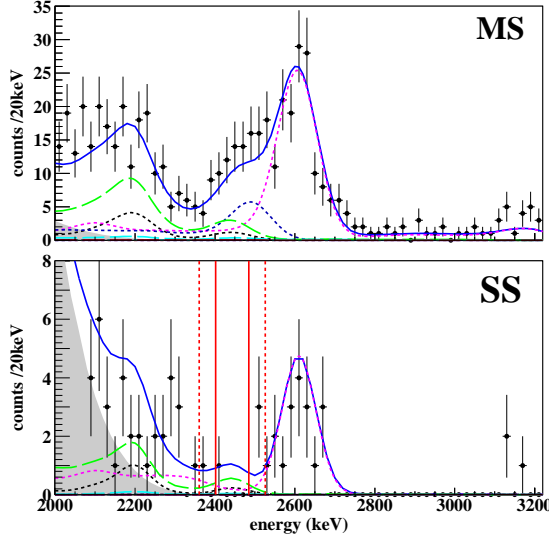


FIG. 3: Energy spectra in the ^{136}Xe $Q_{\beta\beta}$ region for multiple-site (top) and single-site (bottom) events. The 1 (2) σ regions around $Q_{\beta\beta}$ are shown by solid (dashed) vertical lines [25].

of 135 μm thick composite film. The outer LS acts as an active shield for external γ 's and as a detector for internal radiation from the Xe-LS or IB. The Xe-LS contains $(2.52 \pm 0.07)\%$ by weight of enriched xenon gas (full weight of xenon is ~ 330 kg). The isotopic abundances in the enriched xenon were measured by residual gas analyzer to be $(90.93 \pm 0.05)\%$ of ^{136}Xe and $(8.89 \pm 0.01)\%$ of ^{134}Xe . Scintillation light is recorded by 1,325 17-inch and 554 20-inch photomultiplier tubes (PMTs). Details of the KamLAND detector are given in Ref. [27]. The energy resolution at 2.614 MeV is $\sigma = (6.6 \pm 0.3)\%/\sqrt{E}$ (MeV). The vertex resolution is $\sigma = 15$ cm/ \sqrt{E} (MeV). The energy spectrum of $\beta\beta$ decay candidates is shown in Fig. 5. Unexpectedly detected background ($\text{BI} \approx 10^{-4}$ counts/keV \cdot kg \cdot yr) is \sim two order of magnitude higher than estimated background using previous data of KamLAND detector. Nevertheless quite good results for 2ν decay of ^{136}Xe were obtained. The measured $2\nu\beta\beta$ decay half-life of ^{136}Xe [26] is:

$$T_{1/2}(2\nu, ^{136}\text{Xe}) = [2.30 \pm 0.02(\text{stat}) \pm 0.12(\text{syst})] \cdot 10^{21} \text{ yr} \quad (3)$$

This is consistent with the result obtained by EXO-200 [6, 25]. For $0\nu\beta\beta$ decay, the data give a lower limit of $T_{1/2}(0\nu, ^{136}\text{Xe}) > 6.2 \cdot 10^{24}$ yr (90% C.L.) [26], which corresponds

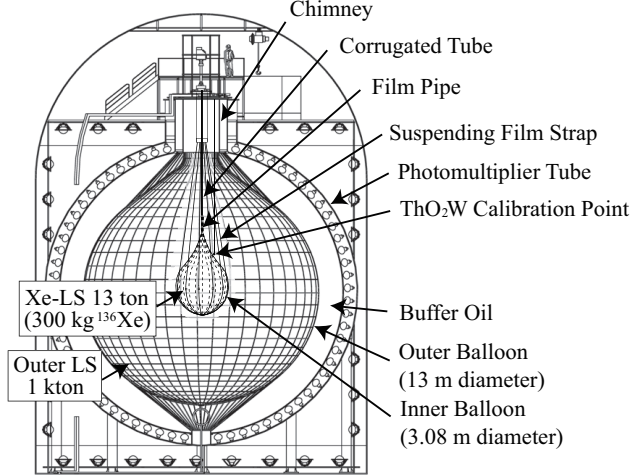


FIG. 4: Schematic diagram of the KamLAND-Zen detector [7].

to limit, $\langle m_\nu \rangle < 0.22 - 0.6$ eV using NME values from [18–20, 22, 24]. Strong limits on neutrinoless double beta decay with emission of Majoron were obtained too (for different modes). In particular, a lower limit on the ordinary Majoron emitting decay (spectral index $n = 1$) half-life of ^{136}Xe was obtained as $T_{1/2}(0\nu\chi^0, ^{136}\text{Xe}) > 2.6 \cdot 10^{24}$ yr at 90% C.L. The corresponding upper limit on the effective Majoron-neutrino coupling constant, using a range of available nuclear matrix calculations, is $\langle g_{ee} \rangle < (0.8 - 1.6) \cdot 10^{-5}$. This is most strong limit on $\langle g_{ee} \rangle$ from $\beta\beta$ decay experiments.

Now the Collaboration undertakes efforts to decrease the background. In principle, the background can be lowered approximately in 100 times. If it will be done, sensitivity of experiment will essentially increase and for 3 years of measurements will be $T_{1/2} \sim 2 \cdot 10^{26}$ yr that corresponds to sensitivity to neutrino mass, $\langle m_\nu \rangle \sim 0.04 - 0.11$ eV. After end of the first phase of the experiment the phase 2 is planned (see the section III. F).

D. GERDA-I [28]

GERDA is a low-background experiment which searches for the neutrinoless double beta decay of ^{76}Ge , using an array of high-purity germanium (HPGe) detectors isotopically enriched in ^{76}Ge [29]. The detectors are operated naked in ultra radio-pure liquid argon, which acts as the cooling medium and as a passive shielding against the external radiation. This innovative design, complemented by a strict material selection for radio-purity, allows to

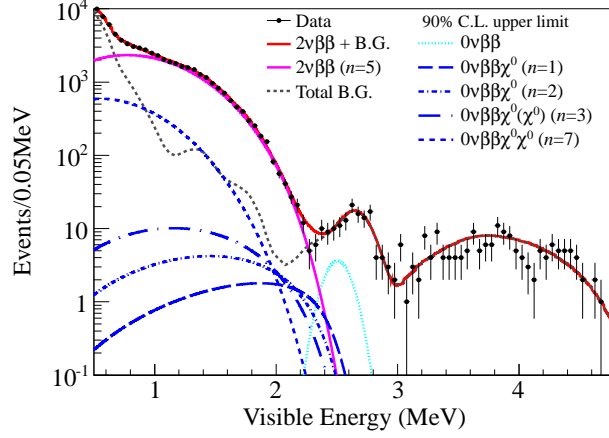


FIG. 5: . Energy spectrum of selected $\beta\beta$ decay candidates (data points) together with the best-fit backgrounds (gray dashed lines) and $2\nu\beta\beta$ decay (purple solid line), and the 90% C.L. upper limit for $0\nu\beta\beta$ decay and Majoron-emitting $0\nu\beta\beta$ decays for each spectral index. The red line depicts the sum of the $2\nu\beta\beta$ decay and background spectra. Figure is taken from [26].

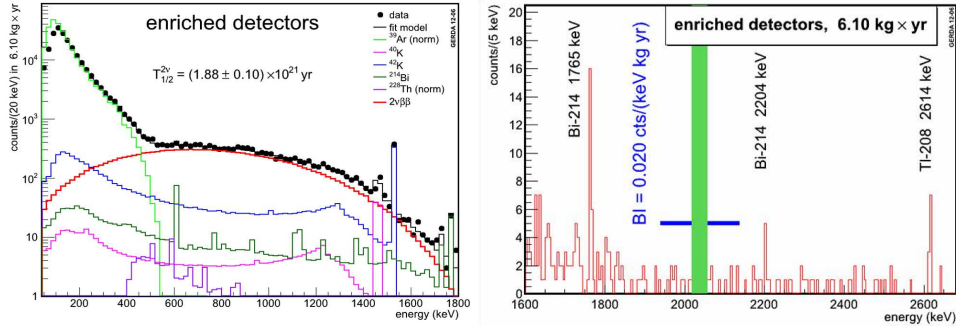


FIG. 6: First results from GERDA-I (figures are taken from [30]).

achieve low background level in the region of the Q-value of ^{76}Ge at 2039 keV. The experiment is located in the underground Laboratori Nazionali del Gran Sasso of the INFN (Italy). The Phase I of GERDA recently has been started using eight enriched coaxial detectors (totaling approximately 18 kg of ^{76}Ge). The Phase I comes after a one-year-long commissioning, in which natural and enriched HPGe detectors were successfully operated in the GERDA set-up. GERDA-I measurements have been started in November 2011. Results of first measurement are presented in Fig. 6 (6.1 kg·yr of data).

As can be seen the 2ν decay contribution is already clearly visible ($T_{1/2}(2\nu, ^{76}\text{Ge}) \approx 1.88 \cdot 10^{21}$ yr, preliminary result). Background index in 0ν region is ~ 0.02 c/keV·kg·yr.

Blind analysis will be applied to the 0ν region (which is closed now). First result will be reported in the end of 2012. Sensitivity of GERDA-I with present background is $\sim 2 \cdot 10^{25}$ yr for one year of measurement. In 2013 new ~ 20 kg of HPGe crystals will be added and experiment will be transformed to Phase II (GERDA-II). Description of full scale GERDA experiment is done in Sec. III B.

III. FUTURE LARGE-SCALE EXPERIMENTS

Here seven of the most developed and promising experiments which can be realized within the next few years are discussed (see Table II). The estimation of the sensitivity in the experiments is made using NME from [18–24].

A. CUORE [9, 31]

This experiment will be run at the Gran Sasso Underground Laboratory (Italy, 3500 m w.e.). The plan is to investigate 760 kg of $^{nat}\text{TeO}_2$, with a total of ~ 200 kg of ^{130}Te . One thousand low temperature (~ 8 mK) detectors, each having a weight of 750 g, will be manufactured and arranged in 19 towers. One tower is approximately equivalent to the CUORICINO detector [5]. Planned energy resolution is 5 keV (FWHM). One of the problems here is to reduce the background level by a factor of about 15 in relation to the background level achieved in the detector CUORICINO. Upon reaching a background level of 0.01 c/keV·kg·yr, the sensitivity of the experiment to the 0ν decay of ^{130}Te for 5 y of measurements and at 90% C.L. will become approximately 10^{26} yr ($\langle m_\nu \rangle \sim 0.05\text{--}0.13$ eV) - see discussion in [37]. The experiment has been approved and funded. A general test of the CUORE detector, comprising a single tower and named CUORE-0, will start to take data in 2012. The full-scale CUORE will start in ~ 2014 .

B. GERDA [28, 29]

This is one of two planned experiments with ^{76}Ge (along with the MAJORANA experiment). The experiment is to be located in the Gran Sasso Underground Laboratory (Italy, 3500 m w.e.). The proposal is based on ideas and approaches which were proposed for

TABLE II: Seven most developed and promising projects. Sensitivity at 90% C.L. for one (GERDA-I), three (1-st step of GERDA and MAJORANA, SNO+, and KamLAND–Xe) five (EXO, SuperNEMO and CUORE) and ten (full-scale GERDA and MAJORANA) years of measurements is presented. M – mass of isotopes.

Experiment	Isotope	M, kg	Sensitivity $T_{1/2}$, y	Sensitivity $\langle m_\nu \rangle$, meV	Status
CUORE [9, 31]	^{130}Te	200	10^{26}	50–130	in progress
GERDA [28, 29]	^{76}Ge	18	2×10^{25}	200–700	current
		40	2×10^{26}	60–200	in progress
		1000	6×10^{27}	10–40	R&D
MAJORANA [32, 33]	^{76}Ge	20–30	10^{26}	90–300	in progress
		1000	6×10^{27}	10–40	R&D
EXO [6, 36]	^{136}Xe	~ 175	4×10^{25}	90–240	current
		1000	8×10^{26}	20–55	R&D
SuperNEMO [34, 35]	^{82}Se	100–200	$(1-2) \times 10^{26}$	40–110	construction of first module; R&D
KamLAND–Zen [7, 26]	^{136}Xe	~ 330	2×10^{26}	40–110	current
		1000	10^{27}	18–50	R&D
SNO+ [8]	^{150}Nd	50	6×10^{24}	120–410	in progress
		500	3×10^{25}	55–180	R&D

GENIUS [38] and the GEM [39] experiments. The idea is to place naked HPGe detectors in highly purified liquid argon (as passive and active shield). It minimizes the weight of construction material near the detectors and decreases the level of background. The liquid argon dewar is placed into a vessel of very pure water. The water plays a role of passive and active (Cherenkov radiation) shield. The proposal involves three phases. In the first phase, the existing HPGe detectors (~ 18 kg), which previously were used in the Heidelberg-Moscow [2] and IGEX [3] experiments, are utilized (see Sec. II. D). In the second phase

~ 40 kg of enriched Ge will be investigated. In the third phase the plan is to use ~ 1000 kg of ^{76}Ge . The sensitivity of the second phase (for three years of measurement) will be $T_{1/2} \sim 2 \cdot 10^{26}$ yr. This corresponds to a sensitivity for $\langle m_\nu \rangle$ at the level of $\sim 0.06\text{--}0.2$ eV.

The first two phases have been approved and funded. First phase will be finished in the end of 2012. The second phase setup is in an advanced construction stage and data taking is foreseen for 2013. The results of these steps will play an important role in the decision to support the full scale experiment.

C. MAJORANA [32, 33]

The MAJORANA facility will consist of ~ 1000 HPGe detectors manufactured from enriched germanium (the enrichment is $> 86\%$). The total mass of enriched germanium will be 1000 kg. The facility is designed in such a way that it will consist of many individual supercryostats manufactured from low radioactive copper, each containing HPGe detectors. The entire facility will be surrounded by a passive shield and will be located at an underground laboratory in the United States. Only the total energy deposition will be utilized in measuring the $0\nu\beta\beta$ decay of ^{76}Ge to the ground state of the daughter nucleus. The use of HPGe detectors, pulse shape analysis, anticoincidence, and low radioactivity structural materials will make it possible to reduce the background to a value below $2.5 \cdot 10^{-4}$ c/keV \cdot kg \cdot yr and to reach a sensitivity of about $6 \cdot 10^{27}$ y within ten years of measurements. The corresponding sensitivity to the effective mass of the Majorana neutrino is about 0.01 to 0.04 eV. The measurement of the $0\nu\beta\beta$ decay of ^{76}Ge to the 0^+ excited state of the daughter nucleus will be performed by recording two cascade photons and two beta electrons. The planned sensitivity for this process is about 10^{27} y. In the first step $\sim 20\text{--}30$ kg of ^{76}Ge will be investigated (MAJORANA Demonstrator). It is anticipated that the sensitivity to $0\nu\beta\beta$ decay to the ground state of the daughter nuclei for 3 years of measurement will be $T_{1/2} \sim 10^{26}$ yr. It will reject or confirm the "positive" result from [40–42]. Sensitivity to $\langle m_\nu \rangle$ will be $\sim 0.09\text{--}0.3$ eV. During this time different methods and technical questions will be checked and possible background problems will be investigated. The MAJORANA Demonstrator is being constructed at the Sanford Underground Research Facility (SURF) at the old Homestake gold mine in Lead, SD. The first cryostat is planned for commissioning in 2013.

The Majorana and GERDA collaborations are cooperating in efforts to design a large-mass (~ 1 ton) Ge detector. The configuration of such an experiment will be optimized based on the outcomes of the MAJORANA Demonstrator and GERDA Phase-II.

D. SuperNEMO [34, 35]

The NEMO Collaboration has studied and is pursuing an experiment that will observe 100–200 kg of ^{82}Se with the aim of reaching a sensitivity for the 0ν decay mode at the level of $T_{1/2} \sim (1 - 2) \cdot 10^{26}$ y. The corresponding sensitivity to the neutrino mass is 0.04 to 0.11 eV. In order to accomplish this goal, it is proposed to use the experimental procedures nearly identical to that in the NEMO-3 experiment (see Sec. II. A). The new detector will have planar geometry and will consist of 20 identical modules (7 kg of ^{82}Se in each sector). A ^{82}Se source having a thickness of about 40 mg/cm² and a very low content of radioactive admixtures is placed at the center of the modules. The detector will again record all features of double beta decay: the electron energy will be recorded by counters based on plastic scintillators ($\Delta E/E \sim 8\%$ (FWHM) at $E = 1$ MeV), while tracks will be reconstructed with the aid of Geiger counters. The same device can be used to investigate ^{150}Nd , ^{100}Mo , ^{116}Cd , and ^{130}Te with a sensitivity to $0\nu\beta\beta$ decay at a level of about $(0.5 - 1) \cdot 10^{26}$ yr [34]. The use of an already tested experimental technique is an appealing feature of this experiment. The plan is to arrange the equipment at the new Frejus Underground Laboratory (France; 4800 m w.e.). The construction and commissioning of the Demonstrator (first module) will be completed in 2013–2014.

E. EXO [6, 36]

In this experiment the plan is to implement Moe's proposal of 1991 [43]. Specifically it is to record both ionization electrons and the Ba^+ ion originating from the double beta decay process $^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} + 2e^-$. In [36], it is proposed to operate with 1t of ^{136}Xe . The actual technical implementation of the experiment has not yet been developed. One of the possible schemes is to fill a TPC with liquid enriched xenon. To avoid the background from the 2ν decay of ^{136}Xe , the energy resolution of the detector must not be poorer than 3.8% (FWHM) at an energy of 2.5 MeV (ionization and scintillation signals will be detected). In

the 0ν decay of ^{136}Xe , the TPC will measure the energy of two electrons and the coordinates of the event to within a few millimeters. After that, using a special stick Ba ions will be removed from the liquid and then will be registered in a special cell by resonance excitation. For Ba^{++} to undergo a transition to a state of Ba^+ , a special gas is added to xenon. The authors of the project assume that the background will be reduced to one event within five years of measurements. Given a 70% detection efficiency it will be possible to reach a sensitivity of about $8 \cdot 10^{26}$ yr for the ^{136}Xe half-life and a sensitivity of about 0.02 to 0.06 eV to the neutrino mass. One should note that the principle difficulty in this experiment is associated with detecting the Ba^+ ion with a reasonably high efficiency. This issue calls for thorough experimental tests, and positive results have yet to be obtained. As the first stage of the experiment EXO-200 use 175 kg of ^{136}Xe without Ba ion identification (see Sec. II. B).

F. KamLAND-Zen-2

KamLAND-Zen is an upgrade of the KamLAND setup [27]. The idea is to convert it to neutrinoless double beta decay search by dissolving Xe gas in the liquid scintillator. This approach was proposed by R. Raghavan in 1994 [44]. At the first step this mixture (330 kg of Xe in 13 tons of liquid scintillator) will be contained in a small balloon suspended in the centre of the KamLAND sphere. It will guarantee low background level and high sensitivity of the experiment. This experiment (KamLAND-Zen) is in a stage of a data taking and some more years will proceed (see Sec. II. C). Experiment KamLAND-Zen-2 with 1000 kg of the enriched xenon will be the next step. It is planned to upgrade the existing detector. It is supposed that in the new inner balloon more bright liquid scintillator will be used and the number of PMTs will be increased. All this will allow to improve essentially energy resolution of the detector and, thereby, to increase sensitivity of experiment to double beta decay (see Table II). KamLAND-Zen-2 will start after ~ 2015 .

G. SNO+ [8]

SNO+ is an upgrade of the solar neutrino experiment SNO (Canada), aiming at filling the SNO detector with Nd loaded liquid scintillator to investigate the isotope ^{150}Nd . With

0.1% loading SNO+ will use 0.78 tons of neodymium and contain 43.7 kg of ^{150}Nd with no enrichment. SNO+ is in construction phase with natural neodymium. Data taking is foreseen in 2013–2014. After 3 yr of data taking sensitivity will be $\sim 6 \cdot 10^{24}$ yr (or 0.12–0.41 eV for $\langle m_\nu \rangle$). Finally 500 kg of enriched ^{150}Nd will be used (if enrichment of such quantity of Nd will be possible). Planned sensitivity is $\sim 3 \cdot 10^{25}$ yr (or 0.055–0.18 eV for $\langle m_\nu \rangle$).

TABLE III: Best current results concerning the search for $0\nu\beta\beta$ decay. All bounds are given with 90% C.L. The bounds on the effective mass of the Majorana neutrino $\langle m_\nu \rangle$ were obtained using the calculated nuclear matrix elements from [18–24].

Isotope	$E_{2\beta}$, keV	$T_{1/2}$, yr	$\langle m_\nu \rangle$, eV
^{48}Ca	4272	$> 5.8 \times 10^{22}$ [45]	< 14
^{76}Ge	2039.0	$> 1.9 \times 10^{25}$ [2]	$< 0.20 - 0.69$
^{82}Se	2996	$> 3.6 \times 10^{23}$ [12]	$< 0.77 - 2.4$
^{96}Zr	3350	$> 9.2 \times 10^{21}$ [17]	$< 3.9 - 13.7$
^{100}Mo	3034.4	$> 1.1 \times 10^{24}$ [12]	$< 0.29 - 0.70$
^{116}Cd	2813.5	$> 1.7 \times 10^{23}$ [46]	$< 1.16 - 2.16$
^{128}Te	867	$> 1.5 \times 10^{24}$ (geochemistry) ([47, 48])	$< 1.8 - 4.2$
^{130}Te	2527.5	$> 2.8 \times 10^{24}$ [5]	$< 0.35 - 0.77$
^{136}Xe	2458.7	$> 1.6 \times 10^{25}$ [25]	$< 0.14 - 0.38$
^{150}Nd	3371.4	$> 1.8 \times 10^{22}$ [16]	$< 2.2 - 7.5$

IV. CONCLUSION

Best present limits on $0\nu\beta\beta$ decay and on $\langle m_\nu \rangle$ are presented in Table III. It is visible that the most strong limits are received in experiments with ^{136}Xe , ^{76}Ge , ^{100}Mo and ^{130}Te . Considering existing uncertainty in values of NME it is possible to obtain conservative limit $\langle m_\nu \rangle < 0.4$ eV (using conservative EXO-200 value). It is possible to expect that in the next few years sensitivity to $\langle m_\nu \rangle$ will be improved by efforts of experiments of EXO–200, KamLAND–Zen, GERDA–II, MAJORANA–Demonstrator, CUORE–0 several times and will reach values ~ 0.1 – 0.3 eV. Start of full-scale experiments will allow to reach in 2015–2020 sensitivity to $\langle m_\nu \rangle$ at the level 0.01–0.1 eV that will allow to begin testing of inverted

hierarchy region (~ 50 meV). Using modern experimental approaches it will be extremely difficult to reach sensitivity to $\langle m_\nu \rangle$ on the level of $\sim 3\text{--}5$ meV (normal hierarchy region). For this purpose it is required to increase mass of a studied isotope to ~ 10 tons and to provide almost zero level of a background in studied area. Nevertheless it was shown, what even using known today methods such possibility, in principle, exists (see [49]).

-
- [1] Elliott S. R., Hahn A. A., Moe M. K., Phys. Rev. Lett. 59 (1987) 2020.
 - [2] Klapdor-Kleingrothaus H. V. et al., Eur. Phys. J. A 12 (2001) 147.
 - [3] Aalseth C. E. et al., Phys. Rev. D 65 (2002) 092007.
 - [4] Arnold R. et al., Nucl. Instr. Meth. A 536 (2005) 79.
 - [5] Andreotti E., Astropart. Phys. 34 (2011) 822.
 - [6] Ackerman N. et al., Phys. Rev. Lett. 107 (2011) 212501.
 - [7] Gando A. et al., Phys. Rev. C 85 (2012) 045504.
 - [8] Hartnell J., J. Phys. Conf. Ser. 375 (2012) 042015.
 - [9] Gorla P., J. Phys. Conf. Ser. 375 (2012) 042013.
 - [10] Simard L., J. Phys. Conf. Ser. 375 (2012) 042011.
 - [11] Arnold R. et al., Phys. Rev. Lett. 95 (2005) 182302.
 - [12] Barabash A. S., and Brudanin V. B., Phys. At. Nucl. 74 (2011) 312.
 - [13] Arnold R. et al., Nucl. Phys. A 765 (2006) 483.
 - [14] Arnold R. et al., Nucl. Phys. A 781 (2007) 209.
 - [15] Arnold R. et al., Phys. Rev. Lett. 107 (2011) 062504.
 - [16] Argyriades J. et al., Phys. Rev. C 80 (2009) 032501R.
 - [17] Argyriades J. et al., Nucl. Phys. A 847 (2010) 168.
 - [18] Kortelainen M., and Suhonen J., Phys. Rev. C 76 (2007) 024315.
 - [19] Barea J. and Iachello F., Phys. Rev. C 79 (2009) 044301.
 - [20] Simkovic F. et al., Phys. Rev. C 79 (2009) 055501.
 - [21] Rath P. K. et al., Phys. Rev. C 82 (2010) 064310.
 - [22] Rodrigues T. R., and Martinez-Pinedo G. M., Phys. Rev. Lett. 105 (2010) 252503.
 - [23] Kortelainen M., and Suhonen J., Phys. Rev. C 75 (2007) 051303R.
 - [24] Caurier E. et al., Phys. Rev. Lett. 100 (2008) 052503.

- [25] Auger M. et al., arXiv:hep-ex/1205.5608.
- [26] Gando A. et al., Phys. Rev. C 86 (2012) 021601R.
- [27] Abe S. et al., Phys. Rev. C 81 (2010) 025807.
- [28] Cattadori C. M., J. Phys. Conf. Ser. 375 (2012) 042008.
- [29] Abt I. et al., arXiv:hep-ex/0404039.
- [30] Grabmayr P., talk at Int. Conf. Neutrino'2012 (Kyoto, Japan), June 4-9, 2012.
- [31] Arnaboldi C. et al., Nucl. Inst. Meth. A 518 (2004) 775.
- [32] Majorana Collaboration, arXiv:nucl-ex/0311013.
- [33] Wilkerson J. F. et al., J. Phys. Conf. Ser. 375 (2012) 042010.
- [34] Barabash A. S., Czech. J. Phys. 52 (2002) 575.
- [35] Barabash A. S., J. Phys. Conf. Ser. 375 (2012) 042012.
- [36] Danilov M. et al., Phys. Lett. B 480 (2000) 12.
- [37] Alessandria F. et al., arXiv:nucl-ex/1109.0494.
- [38] Klapdor-Kleingrothaus H. V., Hellmig J, and Hirsch M., J. Phys. G 24 (1998) 483.
- [39] Zdesenko Yu. G., Ponkratenko O. A., and Tretyak V. I., J. Phys. G 27 (2001) 2129.
- [40] Klapdor-Kleingrothaus H. V. et al., Mod. Phys. Lett. A 16 (2001) 2409.
- [41] Klapdor-Kleingrothaus H. V. et al., Phys. Lett. B 586 (2004) 198.
- [42] Klapdor-Kleingrothaus H. V. et al., Mod. Phys. Lett. A 21 (2006) 1547.
- [43] Moe M., Phys. Rev. C 44 (1991) R931.
- [44] Raghavan R. S., Phys. Rev. Lett. 72 (1994) 1411.
- [45] Umehara S. et al., Phys. Rev. C 78 (2008) 058501.
- [46] Danevich F. A. et al., Phys. Rev. C 68 (2003) 035501.
- [47] Manuel O.K., in Proc. Int. Symp. "Nuclear Beta Decay and Neutrino (Osaka'86)", (World Scientific, Singapore, 1986), p. 71.
- [48] Barabash A.S., Phys. Rev. C 81 (2010) 035501.
- [49] Barabash A. S., J. Phys. G 39 (2012) 085103.